KINK–BAND FORMATION OF FIBER REINFORCED POLYMER (FRP)

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ABSTRACT

Longitudinal compressive strength of fiber reinforced polymer (FRP) is generally lower than its tensile strength. The non-linearity or the plasticity of composite matrix can be critical in kink–band formation of composite structure. Therefore, unstable behaviours of FRP structures under compressive load and lateral disturbance are investigated and a FEM model is introduced using a 3D 8-ply laminates to represent a 2D fiber-matrix scheme. Unlike other common practice that introduces a certain misalignment (e.g., a sinusoidal imperfection) to trig kink-band formation, perfect straight fiber layers with bi-linear elastic-plastic matrix are used in the FEM model under compressive loads with small lateral loads as perturbation, which will be resulted in an upper bound solution of the buckling load.

1 INTRODUCTION

Longitudinal compressive strength of fiber reinforced polymer (FRP) is generally lower than its tensile strength[1], especially after lateral impacting (CAI). Over past decades, some well-known results are developed to help understand the compressive behavior of fiber reinforced polymer (FRP) composites.

There are many theories about compression failure mechanism of fiber reinforced composites, among which fiber micro buckling failure mechanism is the most widely accepted mechanism. Rosen[2] considers that fiber buckling is the main damage mechanism of compressive failure of composites under linear elastic deformation of resin. Rosen proposes that the compressive strength of composite is related to the shear modulus of resin and volume fraction of fiber. However, according to the theory proposed by Rosen, for only resin material, the compression strength is equal to the shear modulus of resin which is larger than the experimental results. Fleck [3]and Budiansky [4; 5] considered the effects of initial imperfections in fiber alignment and plasticity of resin on the compressive kinking failure. And they propose that the compressive strength of composite could be predicted by the shear modulus, initial fiber misalignments angle and yield strain of composites. This theory is generally accepted in subsequent studies. Niu et al [1; 6] considered that the shear band formed by the resin yield leads to the slight instability of fibers, which is the main constraint mechanism of compressive strength. And then Niu [1] proposed a longitudinal compressive strength criterion for unidirectional fiber composites based on yielding of resin matrix, and derived a mixing law equation for longitudinal compressive strength of unidirectional fiber composites.

Finite element method is an effective tool to simulate the initiation and propagation of buckle behaviour of FRP using matrix yielding and initial imperfections. An extended numerical study about the influence of modelling parameters on the kink band's geometry is presented by Kyriakides[7]. The modelling strategy used a 2D layered approximation assuming a periodic array of a finite number of fiber interposed of layers of matrix, assuming a sinusoidal initial imperfection for all models, with constitutive law for the matrix considered elastic-plastic. Morais [8]proposed a basic-cell method to analysis the micro-buckling for 2D or 3D with assuming a sinusoidal imperfection for fibres, being the matrix elastic-plastic and fibres liner elastic. Vogler et al [9] simulated the kink-band formation under compression and shear using 2D and 3D models where fibres were modelling with global (constant) and local (for kink band initial) imperfections. Pimenta [10] used 2D equivalent micromechanical FE modes of the composite to simulate the kink-band formation which contains fibres with initial geometrical imperfection(sinusoidal, with the amplitude decreasing linearly with the fibre index). Several micromechanical FEM models are developed to simulation the kink-band formation with considering matrix yielding and initial imperfection, assuming periodic boundary condition. However, few literatures are related to initial perfect fibres and free boundary constraint.

Unstable behaviours of FRP structures under compressive load and lateral disturbance are investigated and a FEM model is introduced using a 3D 8-ply laminates to represent a 2D fiber-matrix scheme. Unlike other common practice that introduces a certain misalignment (e.g., a sinusoidal imperfection[10; 11]) to trig kink-band formation, perfect straight fiber layers with ideal elastic-plastic matrix are used in the FEM model under compressive loads with small lateral loads as perturbation, which will be resulted in an upper bound solution of the buckling load.

2 NUMERICAL MODELLING

A perfect 3D ABAQUS FEM model is established to simulate the kink-band formation with 50% fiber volume fraction by 8 fiber layers (element type: SC8R) and 9 matrix layers (element type: C3D8) respectively, as shown in Fig.1. The length, width and thickness of the composite plate are 10 mm, 1 mm and 1.6 mm, respectively. The thicknesses of each fiber element and matrix element are 0.1 mm and 0.05 mm respectively. The Young's modulus of the fiber layer is 200 GPa, the Young's modulus of the matrix layer is 3 GPa, and both Poisson’s ratios are zero in elasticity. The compressive load FY and lateral load F_Z are applied on the model in different steps separately. The Risk method is adopt to analyse the snap-back behaviour of load Fz for the force-displacement plot. The main features of kink-band formation simulation process could be summarized as:

1) A perfect 3D model without any defect like fiber misalignment is established and fiber and matrix layers are arranged in sequence.
2) The material of matrix is regarded as ideal elastic-plastic.
3) The compressive load F_Y is applied on the laminate firstly and held. Then a small lateral load F_Z is also applied.
4) The main parameters that are analysed include: the yield strain, the compressive load F_Y and the lateral load F_Z which will directly affect the formation of kink-band.

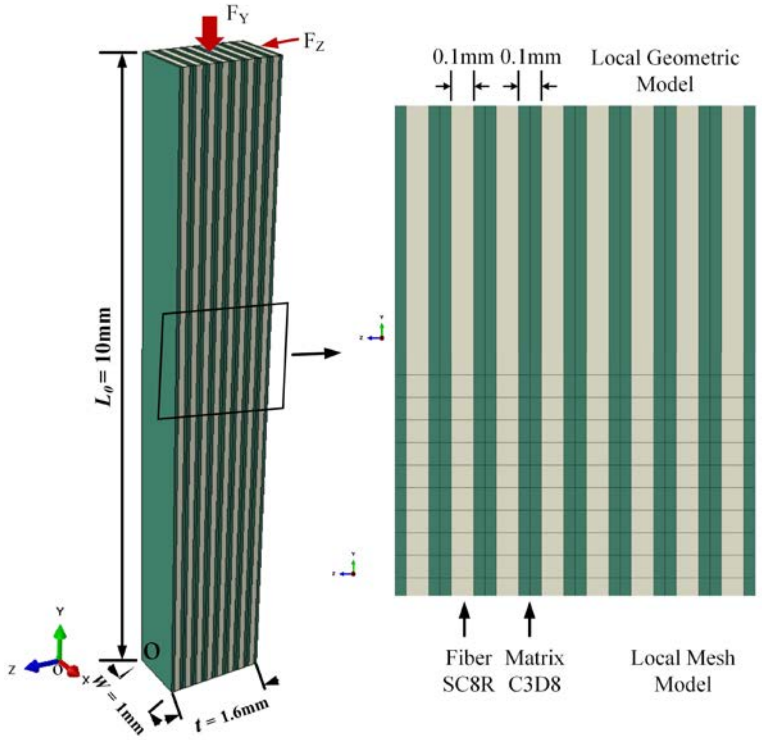


Figure 1: Geometries, meshes and loading conditions of the 3D numerical model.

3 VERIFICATION OF MODEL ASTRINGENCY

3.1 Verification of model astringency in element type

The element type of model is very critical especially related to bending problem. In order to verify the model astringency, the element types of C3D8, C3D20, SC8R are used to solve the eigenvalues of slender column with geometry (1*1*50 mm^3). The theoretical and numerical eigenvalues for the first buckling mode are compared in Table 1. For C3D20 and SC8R, the errors are less than 1% with 1 and 64 element situations. For C3D8, almost 10% error is obtained for only 1 element on cross section. But, with the increase of element number on cross section, the error is also reduced to less than 1%. From the time cost and computational efficiency, C3D8 and SC8R have more advantages. In addition, non-linear and post-buckling analysis with four element type combinations are studied under compressive and lateral loads in Fig.2. It means that the 3D numerical model has good astringency in element type.

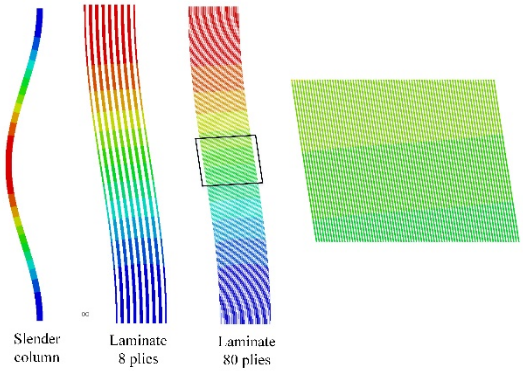
On the other hand, the numerical eigenvalues for 8/80 plies laminates are also solved with two element type combinations (C3D8/SC8R; C3D20/C3D20) as shown in Table 2. The astringency of numerical eigenvalues is good for both C3D8/SC8R; C3D20/C3D20. The buckling modes for slender column, 8 and 80 plies laminates are shown in Fig.2 (a).In addition, non-linear and post-buckling analysis with four element type combinations are studied under compressive and lateral loads in Fig.2 (b). It means that the 3D numerical model has good astringency in element type.

Table 1 Theoretical and numerical eigenvalues for slender column

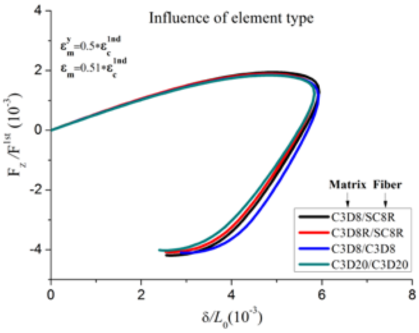
Slender column 1*1*50	Theoretical value	Numerical value					
		1 element on cross section			64 elements on cross section		
		C3D8	C3D20	SC8R	C3D8	C3D20	SC8R
Eigenvalue	262.9	283	262.88	263.17	263.40	262.71	263.94

Table 2 Numerical eigenvalues for 8/80 plies laminates

Laminate	8 plies		80 plies	
	C3D8/SC8R	C3D20/C3D20	C3D8/SC8R	C3D20/C3D20
Numerical Eigenvalue	1831.6	1829.6	1860.3	1859.2



(a)



(b)

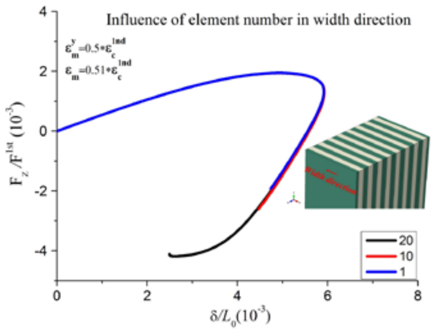
Figure 2: Eigenvalue and non-linear analysis. (a) Buckling mode with different structures; (b) non-linear and post-buckling analysis with four element type combination.

3.2 Verification of model robustness in other aspects

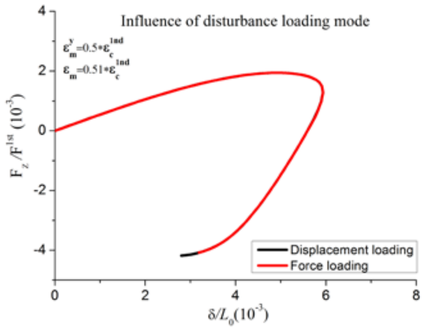
The element number in width direction (1, 10, 20) is discussed in Figure.3 (a). The curves of displacement in Z direction versus disturbance force are shown that the influence of element number in width direction can be ignored. It reduces the element number greatly when the 80 plies of laminate is considered.

For the disturbance loading mode, displacement loading and force loading are both discussed in Figure.3 (b). No matter from the force-displacement curves, or from the overall convergence of the model, there is no difference between the two loading modes.

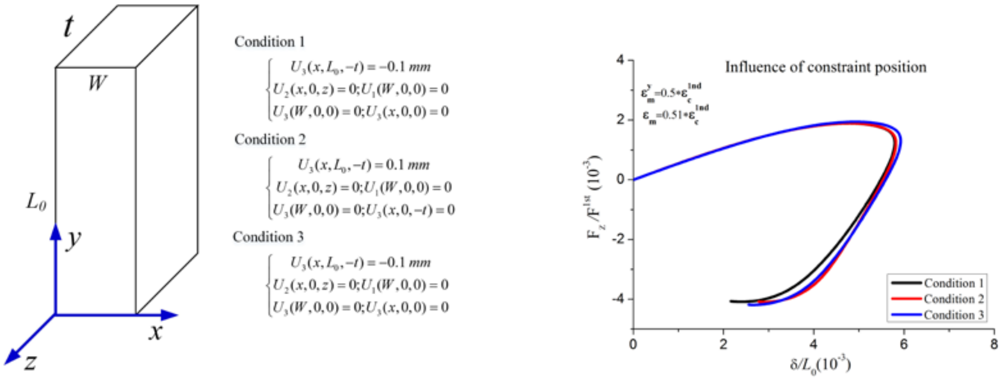
In addition, the boundary condition is also necessary to consider. Three kinds of boundary conditions are shown in Figure.3 (c). The differences among three numerical results are little in Figure.3 (d). In fact, these three boundary conditions bring a very local diversity near the constraint position and has little influence on the globe kink-band formation and force-displacement responses.



(a)



(b)



(c) (d)

Figure 3: Verification of model robustness. (a) element number in width direction; (b) disturbance loading mode; (c) Three kinds of boundary conditions; (d) boundary conditions.

4 KINK-BAND FORMATION

Under the compressive load and lateral disturbance, the formation of kink-band is obtained. The equivalent plastic strain (PEEQ) of compressive composite under a small lateral disturbance with the matrix yield strength at 50% of 1nd eigenvalue and pre-stress at 40% of 1nd eigenvalue is shown in Figure 4. And the following sequence of events for kink-band formation is proposed: 1) elastic domain: after the compressive pre-stress at 40%, the state of matrix and fiber are in elasticity; 2) plasticity beginning: when the lateral loading is applied, the coupling effect of compressive stress and shear stress makes the matrix of middle layer into plasticity firstly; 3) Softening domain: the region of plasticity extends outwards and laminate inclines gradually; 4) Formation of kink-band: with the increase of lateral loading, a typical kink-band formation is developed due to a full plastic deformation in matrix.

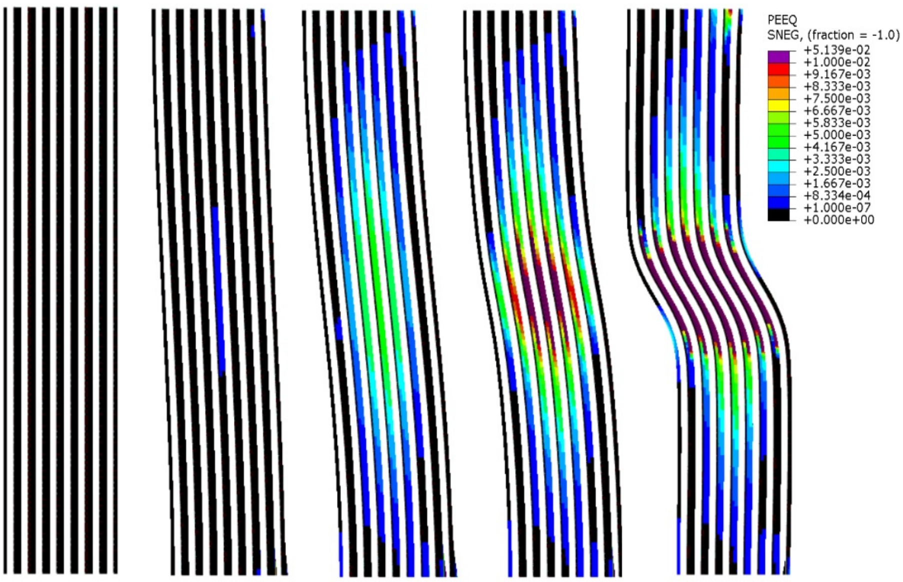


Figure 4: Response of compressive composite under a small lateral disturbance, with the matrix yield strength at 50% of 1nd eigenvalue and pre-stress at 40% of 1nd eigenvalue.

The yield strength of the resin is a very important parameter to judge the compression behavior of CFRP subjected to multi axial compression and shear loading. The force-displacement curves under lateral disturbances have been studied with different yield strengths of matrix as shown in Figure 5. It could be concluded that: The yield deformation of matrix is the key to kink-band formation. If the yield strength of matrix increases from the 50% to 99% (nearly double) of 1nd eigenvalue, the max lateral force needs to increase by 2.3 times to trig a kink-band formation, and the absorbed energy of the composite by the lateral deformation increases by more than 4 times. It means that increasing the yield strength of polymer can effectively improve the capability of fiber reinforced polymer composite resisting the lateral impact load.

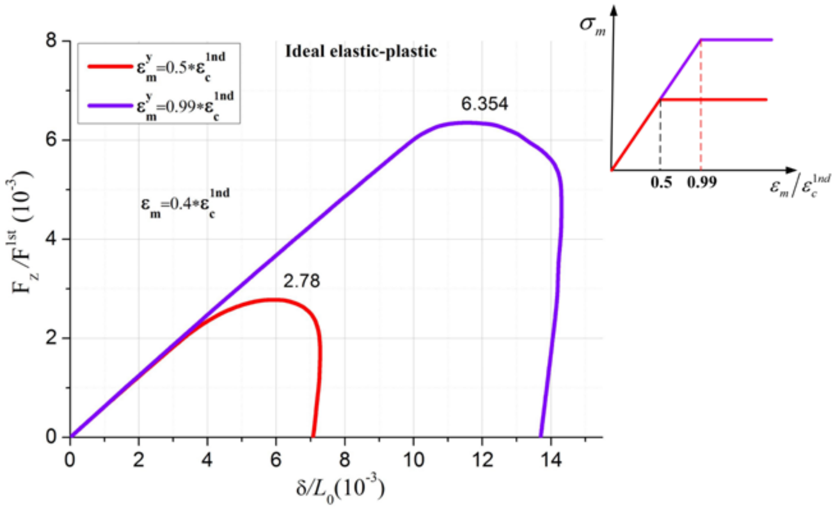


Figure 5: Post-buckling analysis of plates with different matrix yield strain under pre-stress (40% of 1st eigenvalue).

5 CONCLUSION

This paper studies the unstable behavior of composite laminates under lateral disturbance and compression. The formation of kink-band has been obtained by consideration of plasticity of matrix and lateral disturbance. By using the finite element method, the kink-band formation and propagation process has been realized by FEM method. And the influences of yield strength of matrix on the maximum lateral strain have been discussed. It can be inferred that the kink-band with perfect fiber alignment is also occurred when shear band is formed by the resin yield which leads to the slight instability of fibers.

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